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DEVELOPMENT OF CONDENSER MATHEMATICAL MODEL FOR RESEARCH AND DEVELOPMENT OF WAYS TO IMPROVE ITS EFFICIENCY

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Key words: *mathematical model, annular grooves, condenser, failures, steam turbine, augmentation, efficiency*

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DEVELOPMENT OF CONDENSER MATHEMATICAL MODEL FOR RESEARCH AND DEVELOPMENT OF WAYS TO IMPROVE ITS EFFICIENCY

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The condensing unit is one of the most important elements of the steam turbine of a combined heat and power plant. Defects in elements of the condensing unit lead to disturbances in the steam turbine operation, its failures and breakdowns, as well as efficiency losses of the plant. Therefore, the operating personnel need to know the cause of the malfunction and to correct it immediately. There are no diagnostic models of condensers in the Republic of Kazakhstan at the moment. In this regard, a mathematical model of a condenser based on the methodology of Kaluga Turbine Plant (KTP) has been developed. The mathematical model makes it possible to change the input parameters, plot dependency diagrams, and calculate the plant efficiency indicators. The mathematical model of the condenser can be used to research ways for the improvement of the condensing unit efficiency, for diagnostic purposes of the equipment condition, for the energy audit conduction of the plant, and in the training when performing virtual laboratory research. Using static data processing by linear regression method we obtain that the KTP methodology of condenser calculation is fair at cooling water temperature from 20 °C to 24 °C, but at cooling water temperature from 20 °C to 28 °C, the methodology of JSC "All-Russia Thermal Engineering Institute" (JSC "VTI") is used. One of the ways to increase the condenser efficiency has been proposed. It is the heat transfer augmentation with riffling annular grooves on tubes. This method increases the heat transfer coefficient by 2%, reduces the water subcooling of the heating steam by 0.9 °C, and decreases the cooling area by 2%.

Key words: mathematical model, annular grooves, condenser, failures, steam turbine, augmentation, efficiency

INTRODUCTION

The relevance of the work

In the Republic of Kazakhstan, the energy strategy aims at creating an innovative and efficient energy sector. To achieve this goal, it is necessary either to construct new facilities using innovative technologies or by modernizing and adjusting the operating modes of existing equipment of combined heat and power plants (CHPP). One of the most important technological systems is a condensing unit which to a great extent determines the efficiency and reliability of steam turbines and steam turbine plants in general. The condensing unit includes a condenser, circulating cooling water subsystems, condensation drains as well as air extraction, according to PhD thesis in Engineering Science [1]. The condenser unit shall provide preservation of the exhaust steam condensate and its quality, prevention of subcooling of the condensate at the outlet of the condenser against the saturation temperature of the exhaust steam, resulting in the increase of oxygen content in the condensate and loss of heat. It also shall provide the utilization during normal operation, as well as during start-up and shutdown of the power plant provided by its heat balance diagram, discharges of steam into the condenser, hot drains from other equipment and drains of additional water to compensate for steam and water losses, as demonstrated in methodological instructive regulations [2].

The object of research is the CHPP steam turbine condensing unit.

The scientific novelty of the work is as follows:

1. The mathematical model of the condenser has been developed, and its approbation at Almaty CHPP-2 has been conducted.
2. The method of heat transfer augmentation with the application of annular grooves has been proposed.
3. The optimum value of the groove pitch, which enables to increase the heat transfer coefficient, has been chosen.

The theoretical and practical relevance of the research

Theoretical relevance of the research is to expand the knowledge of condenser calculation methodologies, as

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well as the methods of improvement of the condensers' effectiveness.

The practical relevance consists in the fact that the results of the performed work make it possible to solve practical tasks aimed at increasing the efficiency and reliability of the condensing unit. The developed mathematical model of the condenser can be used at diagnostics and monitoring of equipment condition, carrying out the energy audit of the plant, and in the training of personnel.

LITERATURE REVIEW

Such specialists as P.V. Iglin [1], K.E. Aronson [3], S.I. Khaet [4], I.B. Murmansky and others [5], were engaged in their research on the development of the condenser mathematical model.

K.E. Aronson in his thesis for Academic Degree of the Doctor of Technical Sciences [3] and S.I. Khaet in his PhD thesis in Engineering Science [4] developed a diagnostic model of the condenser unit based on the joint characteristic of the condenser and the ejector. The joint characteristic of the condenser and the ejector consists of two sectors. Sector 1 defines the condenser operation at steam consumption close to nominal. Sector 2 defines the ejector operation. Any of the known methodologies can be used to calculate the sector 1.

In the course of the evaluation, we determine pressure losses because of the contamination of the heat transfer surface tubes according to the expression (1) and assess the impact of increased air infiltration on the steam pressure losses in the condenser according to the expression (2).

$$\Delta P_{contam} = P_c^F - P_c \tag{1}$$

$$\Delta P_{air} = P_c - P_c^{calc} \tag{2}$$

The obtained assessments can be useful for the CHPP operating personnel to make a decision on the condenser repair work, according to doctoral thesis [3] and PhD thesis [4].

Besides, K.E. Aronson has developed a refined model of rolled connection of tubes with tubeplates. Calculations by the finite element method made it possible to obtain the technological parameters of the rolling process such as the maximum pressure and the residual pressure in the rolled connection for tubes with different wall thicknesses, which ensure a firm-and-impervious connection between the tubes and the tubeplates, according to doctoral thesis [3].

I.B. Murmansky and others [5] have developed a diagnostic model of components of technological subsystems of steam turbines. The knowledge base is compiled for rotors, bearings, automatic control and protection system of the turbine as well as for other components of the turbine-generator set, for condensing unit equipment and other technological subsystems. The expert system makes it possible to diagnose the condition of various subsystems and components of the turbine-generator set, to eliminate defects in the equipment components and to make recommendations on ways and terms of eliminating defects and reducing the risk of their development. For this purpose, the system uses the experience of specialists. The information from the expert system can be used for adjustment of the turbine operation modes and the optimization of the volume and terms of the equipment repair, as is proven in paper [5].

P.V. Iglin [1] has developed the physical and mathematical model of the condenser based on the refined methodology of the condenser verification calculation, which makes it possible to obtain its characteristics during the pure steam condensation and the steam condensation from the air-steam mixture at variable air infiltrations in any mode of the turbine plant operation, according to PhD thesis [1].

In order to compile the diagnostic model and for the development of activities on improvement of the effectiveness, information on the condition of the equipment must be collected. Thus, K.E. Aronson [3] has developed his own methodology, the essence of which is to conduct open and distance questionnaire with diverse experts. To conduct the survey, the author has developed a questionnaire on the efficiency and reliability of heat-exchange apparatuses. Specialists from the repair and operation staff were engaged as expert consultants, who have worked at the combined heat and power plant for a significant amount of time and hold positions of the middle and top level of the technical staff, according to doctoral thesis [3]. Unfortunately, the author does not provide a sample questionnaire in his thesis. This questionnaire has been developed for heat-exchange apparatuses of power plants in the Russian Federation.

In order to study the condition of the elements of the condensing unit of Almaty CHPP-2, questionnaires have been developed for initial data, the reliability of the condensing unit equipment and analysis of the repair documentation of the plant. Measuring devices and tools for monitoring the init operation have been developed as well.

The questionnaire for the initial data requires completion tables (T-100/120-130-3 turbine condenser's characteristic, ejectors' characteristics, and characteristics of condensate and condensing-water pumps) by the station personnel.

The questionnaire on the condensing unit reliability of steam turbine plants consists of 12 tables. These tables contain the number of apparatuses' damages per year, recovery duration, and the number of replacements during the service life, as well as the frequency of equipment cleaning. The list of damages and their causes of condensation plant elements (the condenser, ejector, circulation pump, and circulation path) is also presented. From results of the analysis of this questionnaire we obtain, that the main damages of the condenser of Almaty

CHPP-2 of Almaty Power Stations JSC are pollution, damage of tubes, fouling of tubeplates, increased air infiltration, and increased oxygen content.

Defects of the equipment of the steam turbine condensing unit of Almaty CHPP-2 with an operating time to the date of April 17, 2020 are introduced into the analysis of the repair documentation. It is possible not to complete the table, but to attach official failure and damage reports of the steam turbine unit equipment.

In the last document, which includes measuring devices and tools for condensing unit operation control, it is necessary to indicate the applied measuring devices and their condition.

The questionnaires will help to collect information on the condition of the elements of the condensing unit of Almaty CHPP-2, identify the most pressing problems and outline the ways to solve these problems.

Now let us consider the ways to increase the condensing unit efficiency.

One of the ways to increase the efficiency of the condensing unit is to reduce the mass consumption of the air-steam mixture due to additional condensation of the steam phase from the composition of the air-steam mixture in special remote-mount coolers. The use of this method allows for the reduction of condenser pressure by 0.4-0.8 kPa and the reduction of oxygen content in the condensate by 30-60 μg/kg. Also, schemes of separate exhaustion of the air-steam mixture from regenerative and network water heaters and the condenser have been proposed. The use of the proposed schemes will allow for reducing the amount of air entering the condenser, intensifying the vacuum in it and reducing the oxygen content in the condensate flowing down from the tube bundle. Besides, the proposed devices provide beneficial use of 0.7-1 MW of heat, previously lost in the condenser, according to PhD thesis in Engineering Science [6]. This method requires additional installation of remote mount coolers.

The efficiency can be improved by increasing the heat transfer coefficient. This is achieved by the use of twisted profiled tubes (TPT) or tubes with annular grooves.

Experimental and theoretical studies on heat transfer augmentation using TPT were conducted. Two characteristic areas were observed for the heat transfer coefficient when steady-state steam condensed on TPT. In the case of low Reynolds numbers of condensate films, the TPT heat transfer coefficient can be 10-15% lower than that of conventional tubes. As both the condensate film and the Reynolds number as well as the profile parameter increase, the heat transfer coefficient increases by up to 50% compared to a conventional tube. During slow steam condensation, the TPT heat transfer coefficient increases by up to 70% compared to a conventional tube. The results of research and industrial tests have shown that the guaranteed effect of increasing the heat transfer coefficient in TPT heat-exchange apparatuses can reach 15% for turbine condensers and 35-40% for low cycle heaters with low-temperature steam power cycle, as demonstrated in paper [7].

The application of tubes with annular grooves leads to a sharp increase in heat transfer on the projecting parts of the tube, which constitute the most of the tube, and as a result, leads to a significant increase in the average heat transfer coefficient outside the tube. The use of knurling also makes it possible to reduce the size of heat-power equipment because knurled tubes, with equal heat output, have a significantly smaller volume compared to smooth tubes, as is proven in paper [8]. This method of heat transfer augmentation is used in this work.

Other ways to increase the condenser efficiency are based on cleaning the tubes from deposits.

MATERIALS AND METHODS

Disturbances in the condensing unit operation may lead to reduced efficiency of the steam turbine plant, as well as to emergency stops of the steam turbine plant as a whole.

In PhD thesis in Engineering Science [9], analyses of damageability of various technological subsystems of the steam turbine plant and damages (failures) of elements of the condensing unit have been carried out. The biggest percent of failures up to 37% are caused by the turbine itself, up to 23% of failures are caused by feed pump failures, up to 13% and 15% belong, respectively, to the condensing unit and turbine regeneration system. At the same time, 9% of failures are caused by pipelines and valves, and 3% of failures are caused by the oil system.

The analysis of damages (failures) of condensing unit elements shows, that the greatest share of failures (46 %) is accounted for condensers, followed by circulation pumps (24 %), ejectors (19 %) and condensing-water pumps (11 %), according to PhD thesis [9].

In this work, the research was carried out by means of mathematical modeling methods.

For research of ways to increase the efficiency of the condenser, it is necessary to have a mathematical model.

There are different methodologies for condenser calculation such as JSC "All-Russia Thermal Engineering Institute" (JSC "VTI"), Institute of Heat Exchange (HEI, USA), Leningrad Metal Works (LMZ), TMZ, Kaluga Turbine Plant (KTP) and Ukhta State Technical University (USTU-UPI) methodologies.

The methodology of the HEI, USA is constantly updated. In its latest edition, the heat transfer coefficient k is determined by dependence (in W/mK) according to standards [10] by the formula:

$$k = k_1 \cdot F_W \cdot F_M \cdot F_C \tag{3}$$

where k_1 is the heat transfer coefficient at water temperature at the condenser inlet, W/mK;

F_W is a correction for water temperature at the condenser inlet;

F_M is a correction for material and wall thickness of condenser tubes;

F_C is the purity coefficient of heat exchange surface.

Heat transfer coefficient k_o according to the methodology of the LMZ is determined by dependence (in W/mK):

$$k_0 = 1096\sqrt{w_w}\sqrt[4]{\frac{t_{1w}+t_{2w}}{2}+17{,}8} \quad (4)$$

Heat transfer coefficient k according to the methodology of the KTP is determined by dependence (in W/mK):

$$k = \frac{1}{\frac{1}{\alpha_w}\frac{d_{out}}{d_{in}} + \frac{1}{\alpha_s} + \frac{d_{out}}{2\lambda_{st}}\ln\frac{d_{out}}{d_{in}} + \sum\frac{\delta_c}{\lambda_c}} \quad (5)$$

where α_w is the heat transfer coefficient on the water side, W/mK;

α_s is the average heat transfer coefficient from the air-steam mixture to the tube wall, W/mK;

λ_{st} and λ_c are thermal conductivity coefficients of the materials of the tube wall (steel) and the contamination layer, respectively, W/mK;

δ_c is the thickness of the contamination layer, m;

d_{out} is the outside diameter of the tube, m;

d_{in} is the inside diameter of the tube, m.

Heat transfer coefficient k according to the methodology of USTU-UPI is determined by dependence (in W/mK):

$$k = \frac{1}{\frac{1}{\alpha_w}\frac{d_{out}}{d_{in}} + \frac{1}{\alpha_s} + 1.15\frac{d_{out}}{\lambda_{st}}\ln\frac{d_{out}}{d_{in}}} \quad (6)$$

where α_w is the heat transfer coefficient on the water side, W/mK;

α_s is the heat transfer coefficient on the steam side, W/mK.

Heat transfer coefficient according to the methodology of JSC "VTI" is determined by dependence (in W/mK):

$$k = 4070 \cdot a \cdot \Phi_w \cdot \Phi_t \cdot \Phi_z \cdot \Phi_\delta \quad (7)$$

where a is the coefficient of heat transfer surface condition,

$\Phi_w \cdot \Phi_t \cdot \Phi_z \cdot \Phi_\delta$ are multipliers which take into account the effect of cooling water velocity, its temperature at the condenser inlet, number of passes, and condenser specific steam load, respectively.

For capacitor calculation using TMZ and LMZ methods, the base value of heat transfer coefficient is determined by VTI method, and then thermal resistance of the contamination layer is added ($R_c=\delta_c/\lambda_c$).

Methodologies of VTI, Institute of Heat Exchange of the USA, LMZ, and TMZ can give an assessment of the average heat transfer coefficient for all heat exchange surface of the condenser on integral modes and design characteristics of the equipment. However, it is impossible to calculate the separate impact of air infiltration and tube contamination using these methods. Methodologies of KTZ and USTU-UPI make it possible to carry out the calculation of the condenser taking into account the separate impact of the air infiltration and contaminations on the steam pressure in the condenser, as demonstrated in thesis [4].

For the development of the condenser mathematical model, the KTP methodology was chosen, because it allows for the separate calculation of heat transfer coefficients on the steam and water sides, but does not take into account the purity of the heat transfer surface.

The mathematical model of the condenser consists of thermal calculation of the condenser and calculation of performance indicators.

Input data for the development of the condenser model are nominal flow rate of exhaust steam ($D_{s,nom}$, kg/s), steam pressure in the condenser (p_s, kPa), nominal cooling water flow rate (G_w, m³/s), and cooling water temperature at the condenser inlet (t_{1w}, °C).

Thermal calculation of the condenser consists in determining the thermal load (Q, W), heat transfer coefficient (k, W/(mK)), heat transfer surface (F, m²), as well as the calculation of the allowable pressure in the tubes (p_s, kPa) for the selected material and geometrical dimensions.

The thermal calculation was performed by the method of iterative calculation. In the first approximation, the saturation temperature is taken for the steam pressure in the condenser. The calculation is performed in two iterations.

The heat transfer coefficient is determined by the formula (5). Heat transfer coefficient on the water side a_w (in W/(mK) is determined by the formula:

$$\alpha_w = 0{,}023\,\mathrm{Re}_w^{0.8}\,\mathrm{Pr}_w^{0.4}\frac{\lambda_w}{d_{in}} \quad (8)$$

where $\mathrm{Re}_w = \frac{\omega_w d_{in}}{\nu_w}$ is the Reynolds number for the wa-ter side of the condenser;

Pr_w is the Prandtl number;

ω_w is the average water velocity in condenser tubes, m/s;

ν_w is the kinematic viscosity coefficient of cooling water, m²/s;

λ_w is the thermal conductivity coefficient of cooling water, W/(mK).

Heat transfer coefficient of the air-steam mixture α_s (in W/mK) is determined by the formula:

$$\alpha_s = 0{,}56\overline{\alpha_s}\varepsilon^{-0{,}05} \quad (9)$$

where $\overline{\alpha_s} = 19\Pi^{0{,}1}Nu^{-0.5}(1+\frac{z}{2})^{0.33}(\overline{s})^{0.15}\alpha_{Nu}$ is the average value of heat transfer coefficient during steam condensation in a tube bundle, W/mK;

$\varepsilon = \frac{G_{air}}{D_s}$ is the relative air content in steam, kg/kg;

$\Pi = \frac{\upsilon_{\text{med}} \omega_s^2}{\upsilon_s g d_{out}}$ is the complex Π;

$Nu = \frac{\alpha_{Nu} d_{out}}{\lambda_{\text{med}}}$ is the Nusselt number;

$\alpha_{Nu} = 0.728 \sqrt[4]{\frac{r g \lambda_{\text{film}}^3 \cdot 1000}{\upsilon_{\text{film}}^2 \mu_{\text{film}} (t_{out} - t_s) d_{out}}}$ is the heat transfer coefficient by Nusselt, W/(mK);

z is the number of water passes of the main bundles;

$\bar{s} = \frac{s_{nar}}{\pi d_{out} N}$ is the relative perimeter of steam running against the tube bundle.

Thermal load of the condenser Q, kW is determined by the formula:

$$Q = \frac{G_w c_{pw} \Delta t_w * 10^3}{3.6} \quad (10)$$

The surface area F, m² is determined from the equation of heat transfer:

$$F = \frac{Q}{k \cdot \Delta t} \quad (11)$$

where $\overline{\Delta t} = \frac{\Delta t_w}{\ln \frac{t_{out} - t_{1w}}{t_{out} - t_{2w}}}$ is the average logarithmic mean temperature difference of heat transfer agents in the condenser, °C.

The subcooling of cooling water to saturation temperature is determined by the formula:

$$\delta t = \frac{t_{2w} - t_{1w}}{\exp(\frac{3.6kF}{G_w c_{pw} * 1000}) - 1} \quad (12)$$

We specify the saturation temperature according to the formula $t'_{sat} = t_{2w} + \delta t$. The discrepancy of saturation temperature calculation is 0.168%, which corresponds to the standards.

Mathematical model of the condenser is one of the modules of "CHA" software product. ("Convective heat exchange, Heat-exchange apparatuses, Augmentation") described in the collection of articles [11]. The structure of "CHA" software product includes the following modules: information and reference database on convective heat exchange, mathematical models of heat-exchange apparatuses, applications, information and reference database on heat exchange at phase transitions. It is also implemented in Microsoft Excel spreadsheet application. Besides the condenser, there are mathematical models of air heater, oil cooler, heavy fuel oil heating apparatus, evaporator, regenerative heaters, and steam-jet ejector.

Practical application of the mathematical model of the condenser makes it possible to significantly expand the possibilities of the comprehensive analysis of operating modes of turbines of combined heat and power plants, carrying out diagnostics of condensers, causes of power plants limitations in summer, etc. The results of the practical application of the mathematical model have confirmed its almost complete adequacy to the physical processes taking place in condensers.

The developed mathematical model is universal; it can be used for any types of steam turbine condensers; it is also easy in use and relevant.

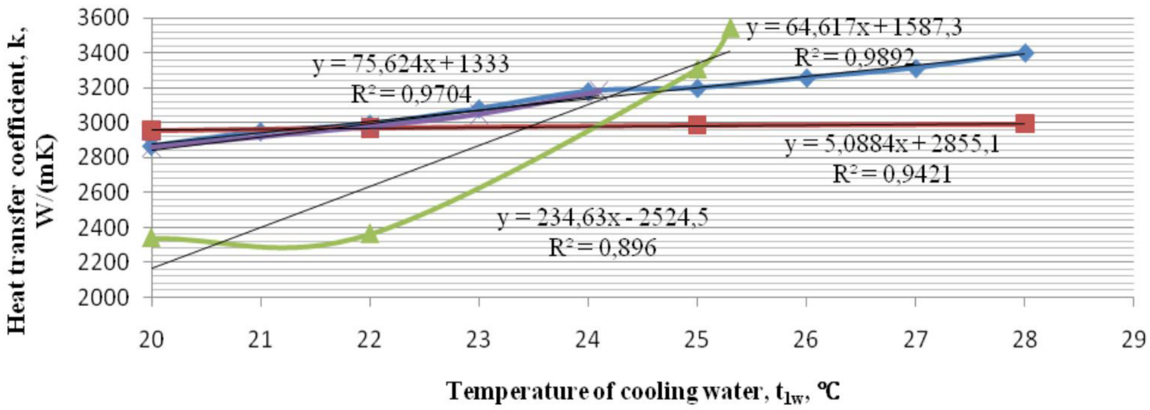
RESULTS

The developed mathematical model of the condenser was tested at Almaty CHPP-2 on the KG2-6200 condenser of steam turbine T-100/120-130-3. Table 1 represents the results of the condenser thermal calculation.

It can be seen from Table 1 that the model's heat transfer coefficient differs by 2%, subcooling of cooling water to saturation temperature differs by 0.8%, steam pressure in the condenser's steam space differs by 4%, surface area differs by 0.7%, tubes length differs by 4%, and tubes number differs by 0.18%, thermal load by 2%. Comparison of the obtained results with station data has revealed that the mathematical model is adequate to the station condenser.

Table 1: Results of the condenser thermal calculation

No.	Description	Notation	Unit of measurement	Value	
				Model	Real apparatus
1	Average value of the heat transfer coefficient of the condenser surface by formula (5)	k	W/(mK)	2850	2907
2	Subcooling of cooling water to saturation temperature by formula (12)	δt	°C	3.5	3.53
3	Steam pressure in condenser steam space at t_{out}	p_c	kPa	5.6	5.37
4	Condenser surface area by formula (11)	F	m²	6135	6180
5	Thermal load by formula (10)	Q	kW	197031	200972
6	Condenser tube length $L = \frac{F}{\pi d_{out} N}$	L	m	13.5	14.1
7	Number of tubes $N = \frac{Qz}{\rho_w * 0,785 d_{in}^2 w_w}$	N	pcs	5570	5560



■ Methodology of VTI;

♦ Performance standard;

▲ Methodology of HEI;

x Methodology of KTP

Figure 1: Dependence of heat transfer coefficient on cooling water temperature

Figure 1 represents the dependence of heat transfer coefficient on cooling water temperature.

The design temperature operation mode of turbine condenser of Almaty CHPP-2 of Almaty Power Stations JSC assumes the temperature of circulating water equal to 20 °C at the inlet and 30 °C at the outlet. The actual temperature mode provided by the plant's cooling tower installation gives temperatures of 24-28 °C at the inlet and 33-37 °C at the outlet. The average excess of temperatures over the normative ones is equal to 4-5 °C (in 2018, the average water temperature at the condenser inlet was 25.2 °C). This leads to a decrease in the technical and economic performance of the turbines due to the loss of vacuum.

With temperature change at the condenser inlet from 20 °C to 25 °C, the typical energy vacuum loss is 0.015 kp/cm^2. This leads to an increase in fuel consumption in the power plant by about 3 g/kWh.

After processing the obtained results using the method of linear regression, we obtain that the condenser calculation by KTP methodology is more suitable than other methods (R2 = 0.97).

However, the KTP methodology cannot be applied for condenser calculation at cooling water temperature t1w above 24 °C. For condenser calculation with cooling water temperature from 24 °C to 28 °C the VTI methodology can be used. This statement is valid only for the condenser KG2-6200 of Almaty CHPP-2 of Almaty Power Stations JSC.

The developed mathematical model makes it possible to carry out the computational experiment: to change parameters, to plot dependency diagrams, and to calculate parameters of the plant efficiency. Mathematical models are developed in Microsoft Excel spreadsheet application.

Our work has proposed a way to increase the condenser efficiency with the use of heat transfer augmentation and the application of annular grooves on the tubes, according to master's thesis [12].

Heat transfer coefficient value during condensation of pure steam for a tube with grooves is described by the expression [13]:

$$\alpha_s = \alpha_{sm} \cdot 2{,}469 \cdot (1 - \frac{R}{D_H}) \cdot (1 - 0{,}379 \cdot \frac{t}{D_H}) \cdot$$

$$\cdot \exp[3{,}65 \cdot (1 - \frac{d_H}{D_H})] \quad (13)$$

where the surface heat-transfer coefficient during condensation of pure steam for a smooth tube a_{sm} is described by the expression:

$$\alpha_{sm} = 0{,}725 \cdot \sqrt[4]{\frac{r \cdot \rho_{film}^2 \cdot g \cdot \lambda_{film}^3}{\mu_{film} \cdot (T_H - T_t) \cdot D_H}} \quad (14)$$

Formula (13) is valid for:

$$\frac{d_H}{D_H} = 0{,}89 \div 0{,}95; \frac{t}{D_H} = 0{,}283 \div 0{,}37; \frac{R}{D_H} = 0{,}5 \div 1.$$

Using a mathematical model of the condenser, the condenser parameters were calculated before and after the application of augmentation (Table 2).

As can be seen from Table 1, the heat transfer coefficient has increased by about 2%. The cooling surface area has decreased by about 2%. Subcooling of water to the saturation temperature of heating steam has decreased by 0.9 °C, the hydraulic resistance of the condenser on the water side has decreased by 1 kPa, and the volume-to-size ratio has increased by 1.5 times. This means that the application of annular grooves (internal turbulence stimulators) has increased the energy efficiency of the condenser.

Table 2: Results of calculation of condenser parameters before and after application of augmentation (according to the master's thesis [12])

No.	Description	Values	
		Before augmentation	After augmentation
1	Cooling surface area, F, m² by formula (11)	2850	2907
2	Heat transfer coefficient, k, W/(mK) by formula (5)	4086	4168
3	Required number of tubes in the condenser, N, pcs $N = \frac{Qz}{\rho_w * 0{,}785 d_{in}^2 w_w}$	5570	5570
4	Subcooling of water to the saturation temperature of heating steam, δt, °C by formula (12)	3	2,1
5	Hydraulic resistance of the condenser on the water side, H_c, kPa $H_c = z \cdot (\lambda \cdot \frac{l}{d_{in}} + \xi) \cdot \frac{\rho_w \cdot \omega_w^2}{2 \cdot g} + \frac{\rho_B \cdot \omega_{gr}^2}{2 \cdot g}$	4	3
6	Volume-to-size ratio, k_{FV}, m²/m³ $k_{FV} = \frac{F}{V_{TA}}$	37	54

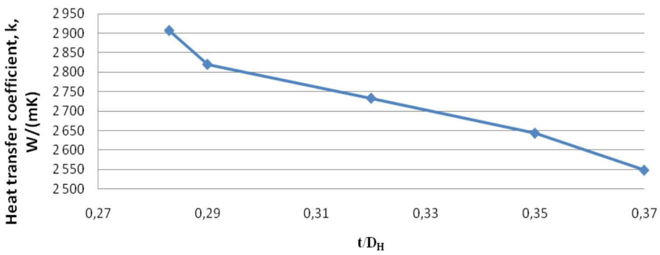


Figure 2: Dependence of the heat transfer coefficient on the change in pitch of annular grooves

Figure 2 illustrates the dependence of the heat transfer coefficient k on the change in pitch of annular grooves t. Figure 2 demonstrates that the heat transfer coefficient decreases as the pitch of the annular grooves increases. The optimal value of the pitch is t/D_H= 0.283, at which the heat transfer intensifies.

The use of annular grooves facilitates the organized drainage of condensate, reduces the thickness of the film and condensate on the tops of projections and, accordingly, increases the intensity of heat transfer during steam condensation.

DISCUSSION

The Republic of Kazakhstan has not yet developed and applied any diagnostic models of the condenser. Therefore, we were faced with the task of developing a mathematical model of the condenser. The development of the mathematical model took into account the experience of other authors, the specific features of our country (specifically the city of Almaty, because the city is located in the seismic zone), the possibility of collecting information and conducting experiments.

When developing the mathematical model of the condenser, the methodology of KTP was used because it was more suitable for the conditions of Almaty CHPP-2 of Almaty Power Stations JSC ($R2$=0.97) and later on for the heat transfer augmentation. Many authors, such as P.V. Iglin [1], K.E. Aronson [3], S.I. Khaet [4], have used the methodology of VTI when developing the diagnostic model. The methodology of KTP has a disadvantage which lies in the fact that at any change of one of the process parameters it is necessary to specify the values of thermophysical properties of water and the condensate film depending on the temperature. There is no such disadvantage in the methodology of KTP.

The specific feature of our work in comparison with other works is that the mathematical model of the condenser is included in the software product "KTI", which has applications with values of thermophysical properties of water and water steam depending on temperature.

The developed mathematical model was used for heat transfer augmentation with the application of annular grooves. This method of efficiency increase can be used when designing a condenser or when completely replacing the tubes in the condenser.

According to the results of calculations (Figure 2), the heat transfer coefficient varies depending on the groove pitch. With value t/D_H = 0,283, the heat transfer coefficient increases by 2%. With changes in groove depth and rounding radius of projecting parts of tubes, the value of heat transfer coefficient practically does not change. This is not the case of the research [8] where the heat transfer coefficient is greater the deeper the grooves, the smaller their pitch and the smaller the rounding radius of projecting parts of tubes R. The optimal value is t/D_H = 0.37 in this case. Such difference can be explained by the fact that we conducted a study on the KG2-6200 condenser and the author of the paper [8], unfortunately, does not indicate the type of condenser.

CONCLUSION

The paper presents an available mathematical model of the condenser. For the development of the mathematical model of the condenser, the methodology of KTP has been chosen. The mathematical model of the condenser has been tested at Almaty CHPP-2. According to the results of the calculation, it can be seen that the model is fully adequate to the station equipment: the model's heat transfer coefficient differs by 2 %, the subcooling of cooling water to the saturation temperature differs by 0.8 %, steam pressure in the condenser's steam space differs by 4 %, surface area differs by 0.7 %, tubes length differs by 4 %, and the number of tubes differs by 0.18 %.

The mathematical model of the condenser can be further used to develop ways to improve the efficiency of the plant, to diagnose the condition of the equipment and for timely troubleshooting in its operation, as well as to conduct energy audits of the plant. Besides, the available mathematical model can be used in the process of thermal power engineering specialists training while performing virtual laboratory works. This mathematical model of the condenser will be used by the employees at Almaty CHPP-2 of Almaty Power Stations JSC.

The method of condenser heat transfer augmentation with the application of annular grooves on tubes has been proposed. This method has significantly increased the efficiency of the condenser (heat transfer coefficient has increased by 2%). This method can be applied both in the case of the full replacement of tubes and at the design stage.

It has been determined that when the groove pitch increases, the heat transfer coefficient decreases. Therefore, the value t/D_H= 0.283 is optimal.

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